Cold quadrupole vibration measurements at CMTB using geophones

Ramila Amirikas, Alessandro Bertolini,
Wilhelm Bialowons, Markus Kubczigk
DESY

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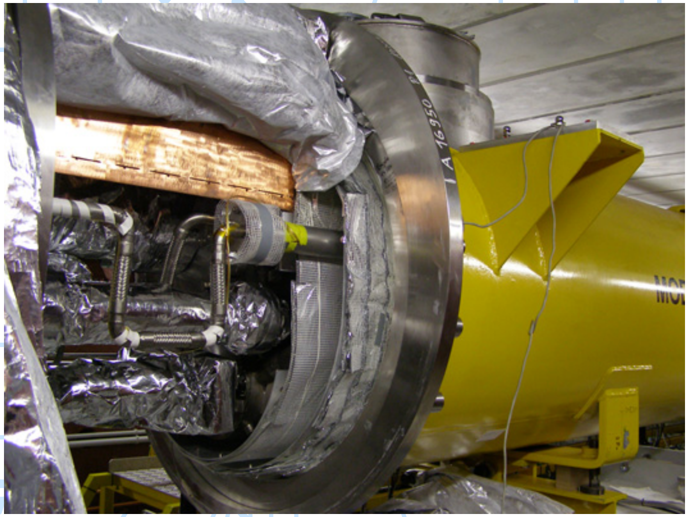
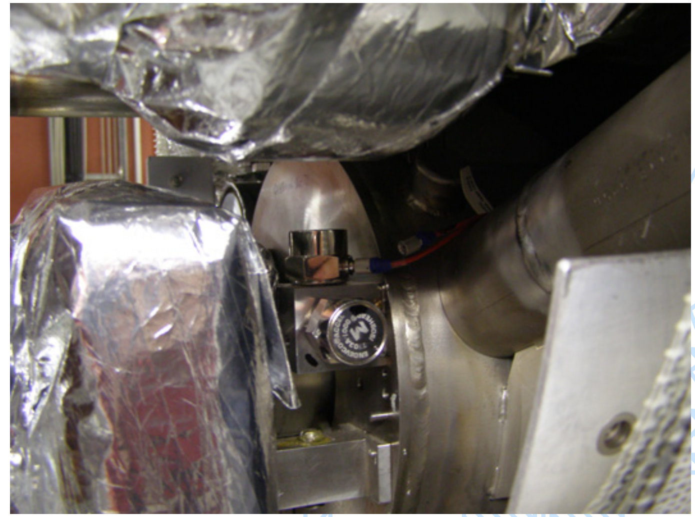
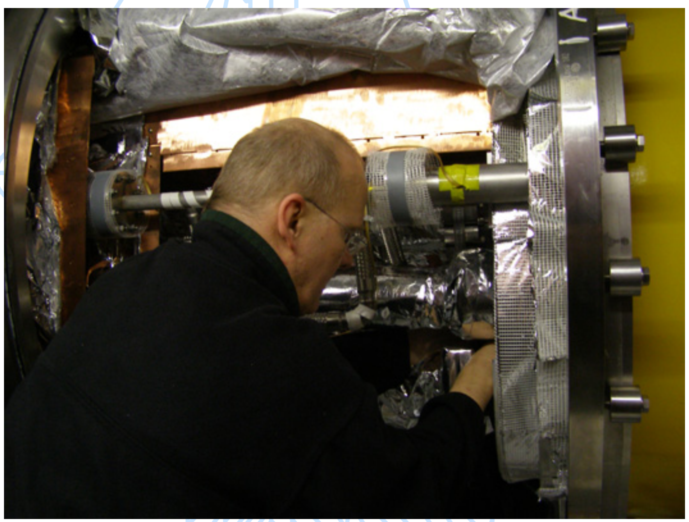
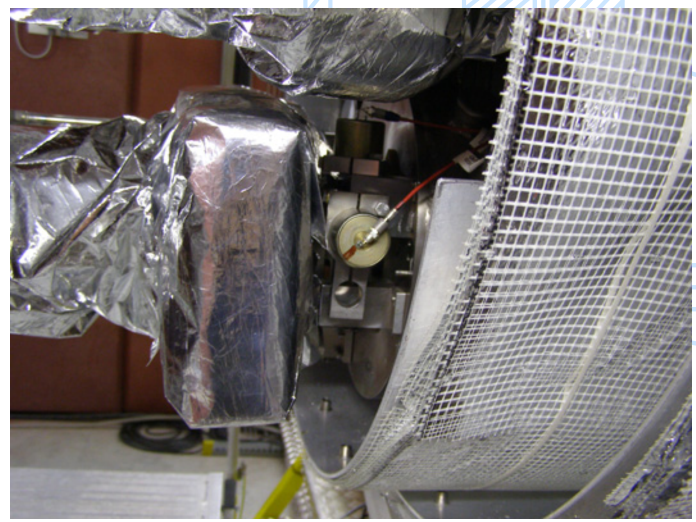
The experiment

Two new seismic sensors (geophones) were installed aboard the Module 6 quadrupole for the 10/11th thermal cycles, from February 21st to March 8th.









Test geophone behaviour at 4 K inside a fully operating cryomodule

• on-board seismic sensor with adequate noise level down to below 1 Hz potentially available for quad and cavities.

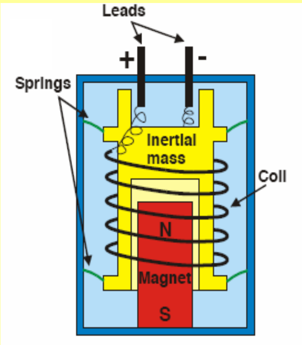
• behaviour unknown, never been tested by the manufacturer in these extreme conditions, the company recommends use of the device down to -40°C, only one cryogenic application cited in literature.

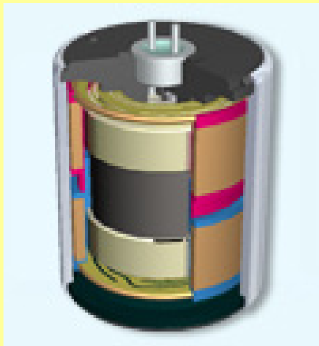
• the very robust and mature (~30 years) design was encouraging and the test has been successful.

Quadrupole vibration measurements at 4 K

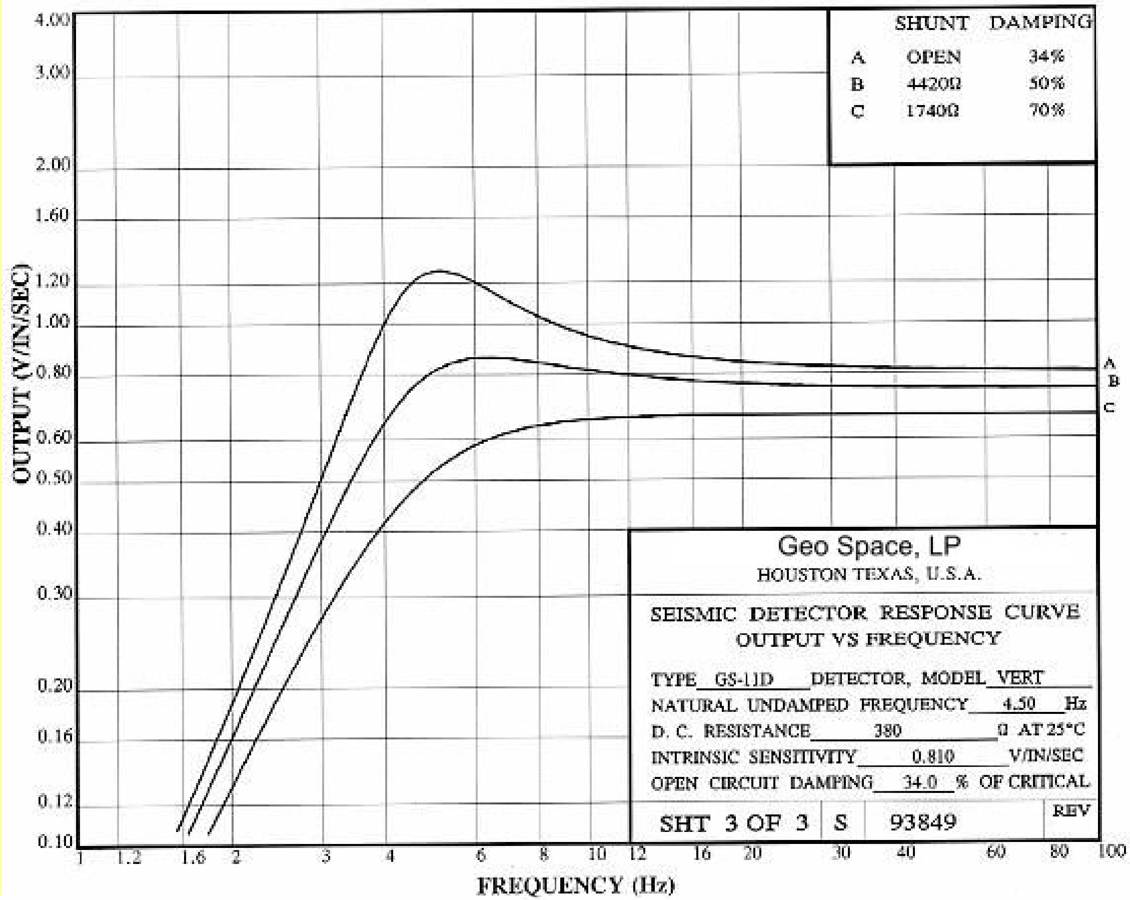
• chance to give a first quantitative (from 1 Hz) evaluation of the impact of cryogenic plant and high gradient RF on the quadrupole vibration level, not possible so far because of the lack of sensitivity of cooled piezo accelerometers below ~10 Hz

How does it work?





When the geophone case is accelerated, the sensing coil moves with respect to the fixed magnet. The gradient of the magnetic field transforms the relative velocity into an emf (with sensitivity **G**), which can then be put in series with a load resistor $\mathbf{R_d}$ to produce a measurable voltage. The flowing current **I** generates a linear force, opposite to the direction of motion, that provides a strong mechanical damping effect.



Frequency response

The frequency response of output voltage vs case/ground velocity is determined by the sensor mechanics and by the load/damping resistor.

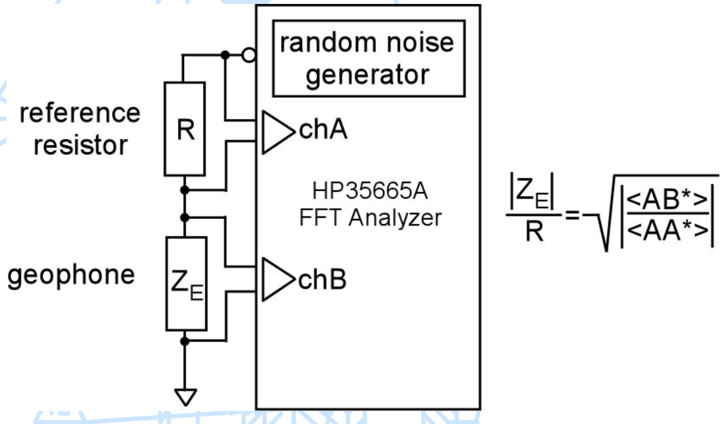
$$\tilde{V}_{out}(\omega) = \left(\frac{R_d}{R_d + R_{coil}}\right) \cdot \frac{-\omega^2 G}{\omega_0^2 - \omega^2 + i\,\frac{\omega\omega_0}{Q_l}}\,\tilde{v}_g(\omega)$$

In-situ calibration method

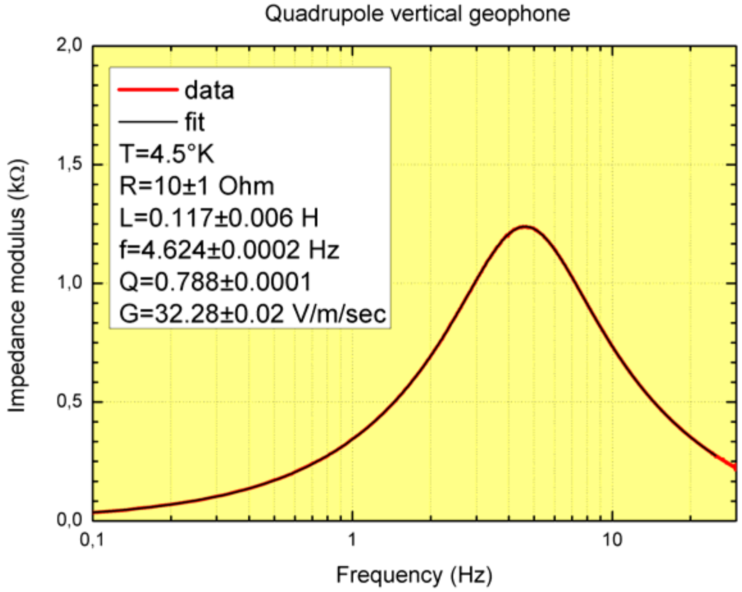
Accurate remote calibration possible using the signal cable itself; no access to the sensor is necessary. By measuring the electrical impedance vs frequency at the output terminals of the sensor we have access to both electrical and mechanical parameters. Only the suspended mass has to be known.

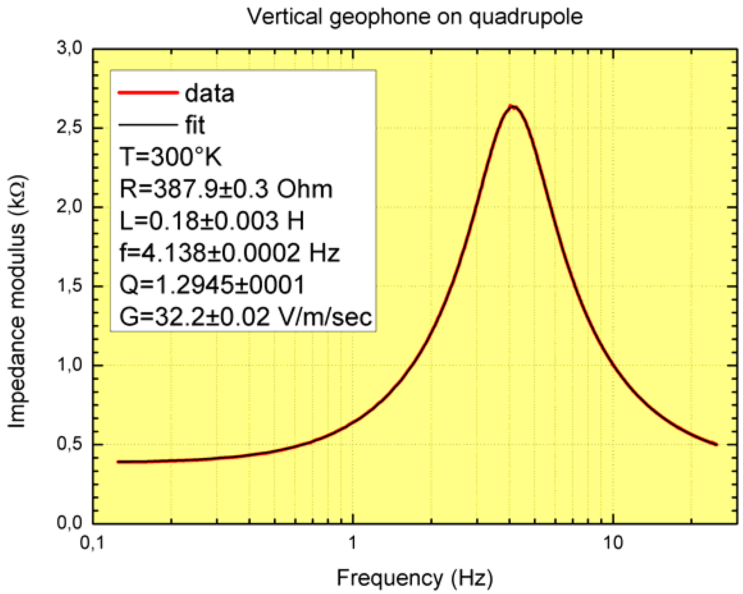
$$Z_E(\omega) = R_{coil} + j\omega L + \frac{j\omega\, G^2/m}{\omega_0^2 - \omega^2 + j\dfrac{\omega\omega_0}{Q_l}}$$

Geophone equivalent impedance



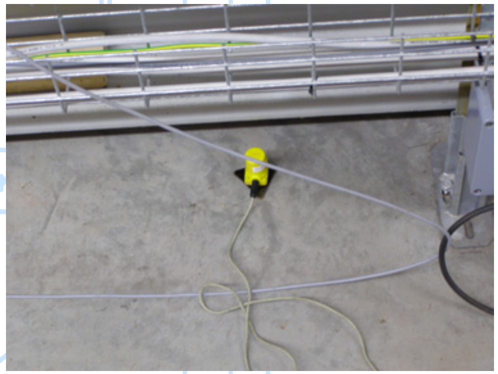
Block diagram of the calibration procedure





The experiment – Setup

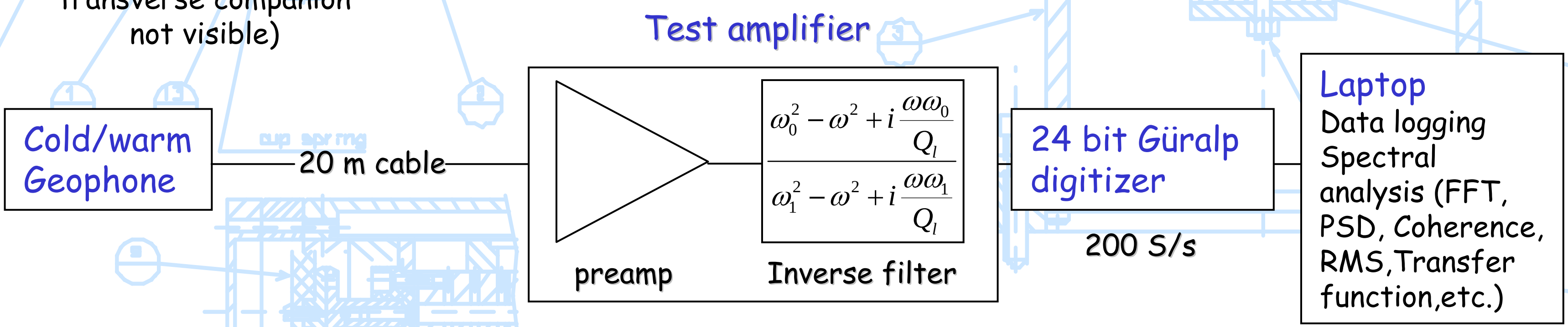
Vessel top vertical sensor (horizontal transverse companion not visible)



Ground vertical sensor (horizontal transverse companion not visible)

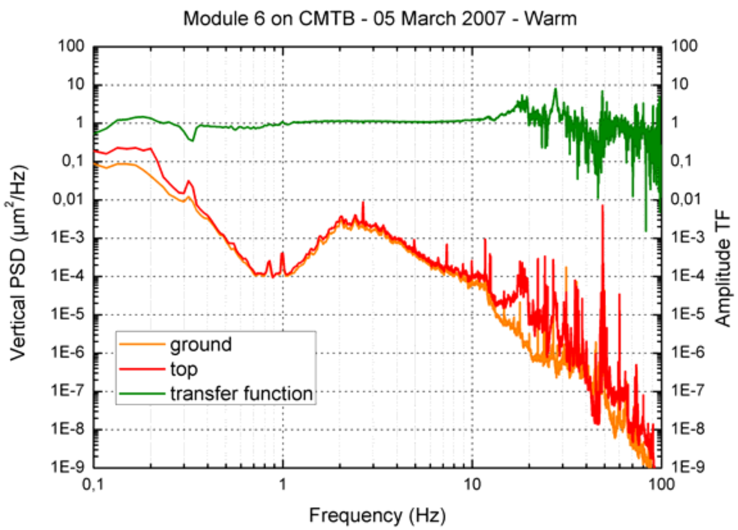
x(t), y(t)	time series of length T, N points each
$X(\nu_i)$, $Y(\nu_i)$	FFT
<XX*>, <YY*>	Estimated displacement power spectral density (PSD)
$\frac{\lvert\langle XY^*\rangle\rvert^2}{\langle XX^*\rangle\langle YY^*\rangle}$	Coherence
$\sqrt{\frac{\lvert\langle XY^*\rangle\rvert}{\langle XX^*\rangle}}$	Transfer function amplitude
$\sqrt{\frac{1}{T}\sum_{i=k}^{N/2}\langle XX^*\rangle(\nu_i)}$	Integrated RMS amplitude at frequency ν_k

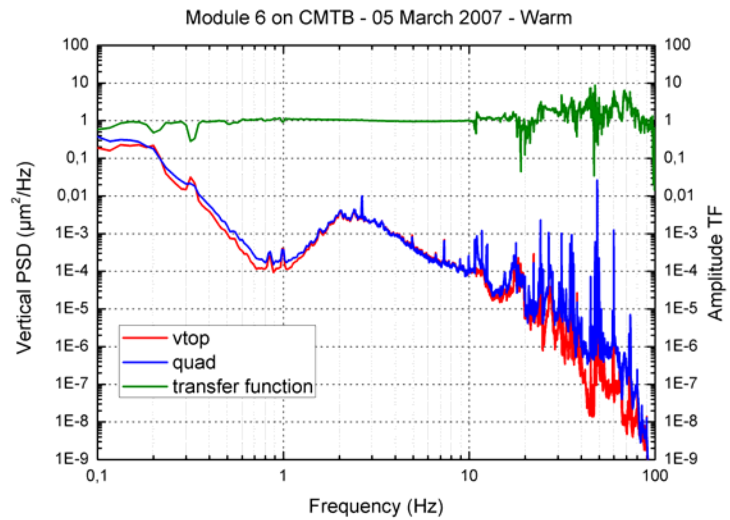
Some definitions



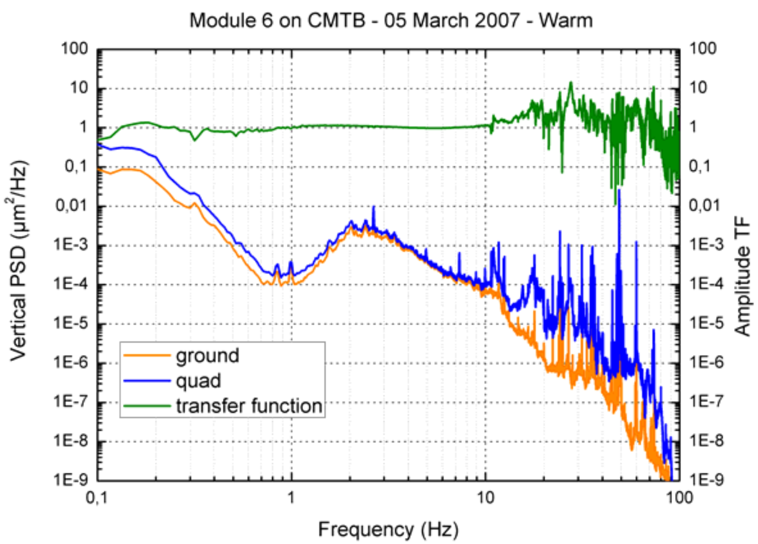
Inverse filtering provides equalization of the geophone response down to 0.35 Hz

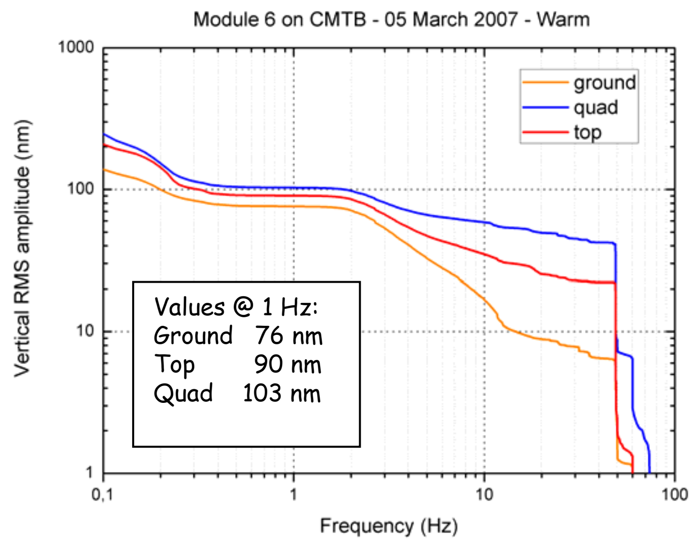
Quadrupole vibrations – Cryomodule warm I





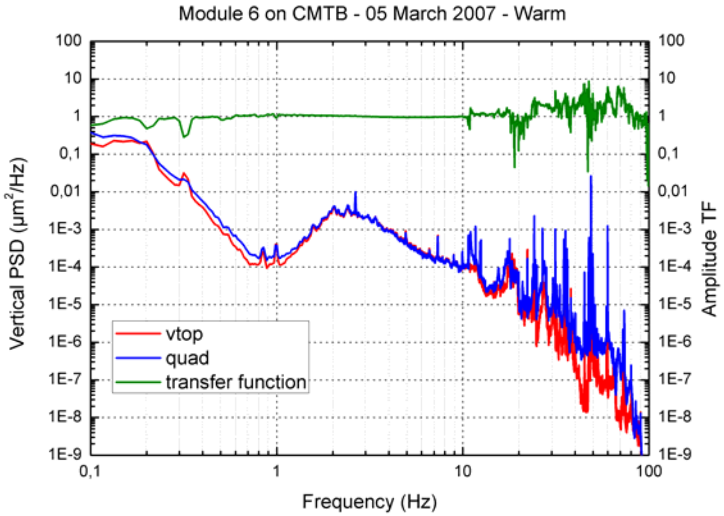
General features of the spectra
Typical DESY site spectrum at low frequencies. Technical noise dominating > 20 Hz; strongest peak from the insulation vacuum pump at 48 Hz. Module vertical resonance at 26 Hz; quad vs top transfer function almost flat below 40 Hz.

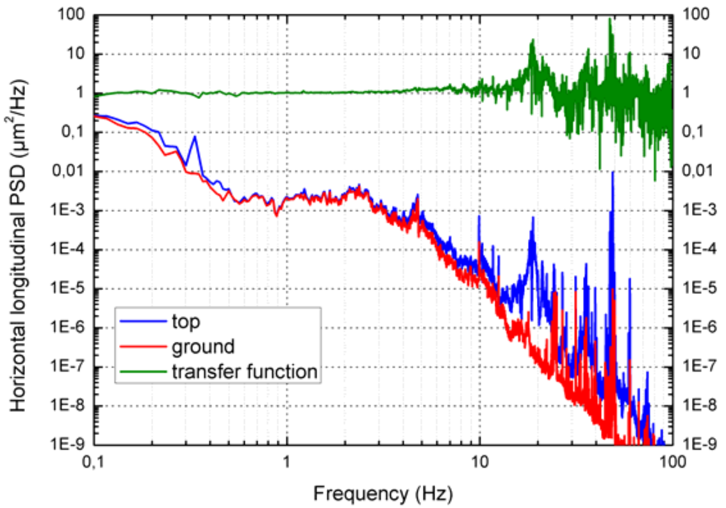


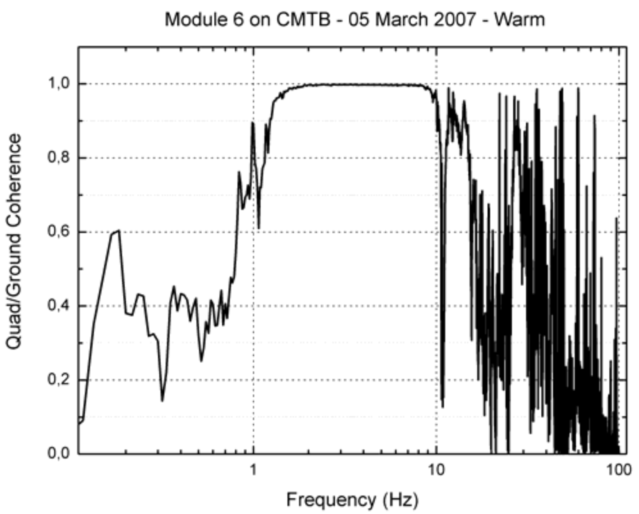


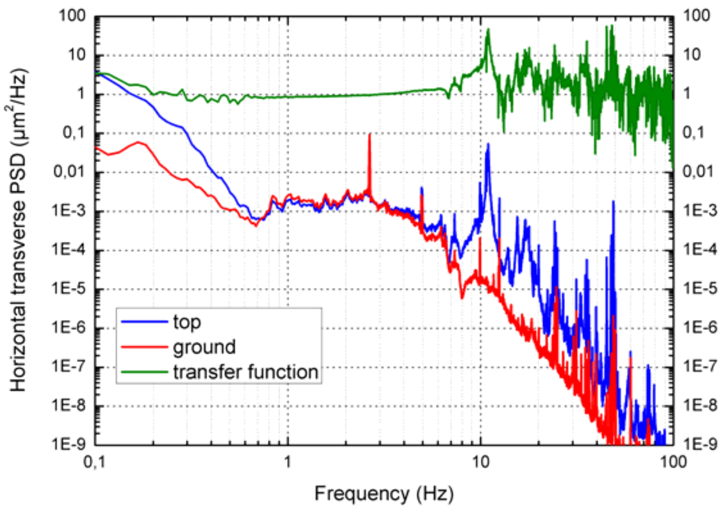
Coupling between axes

Coupling with the 18 Hz horizontal longitudinal mode at both quad and top positions. Coupling with the 11 Hz horizontal transverse rocking mode on quad (due to the off-axis location).





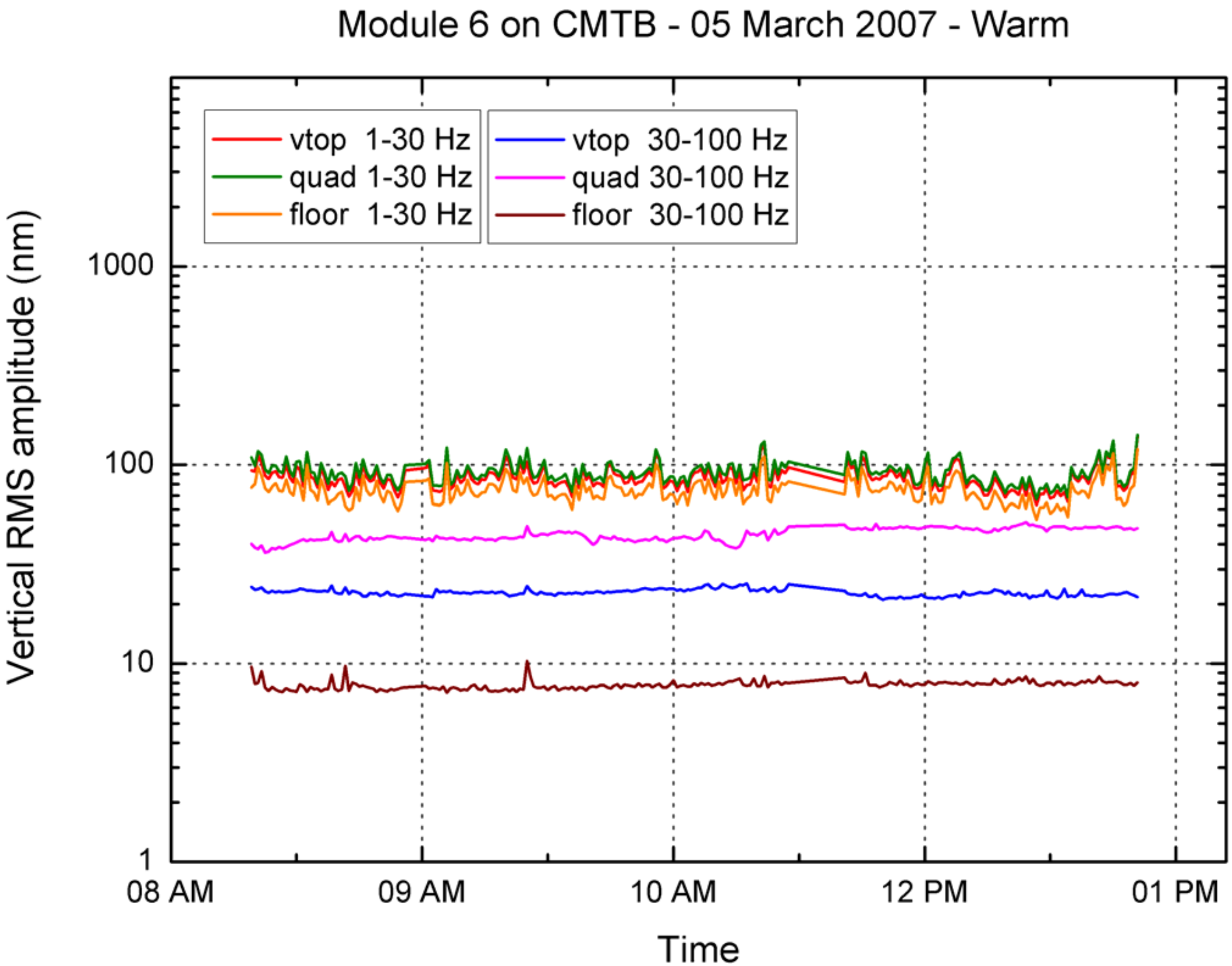




Quadrupole vibrations – Cryomodule warm III

RMS analysis

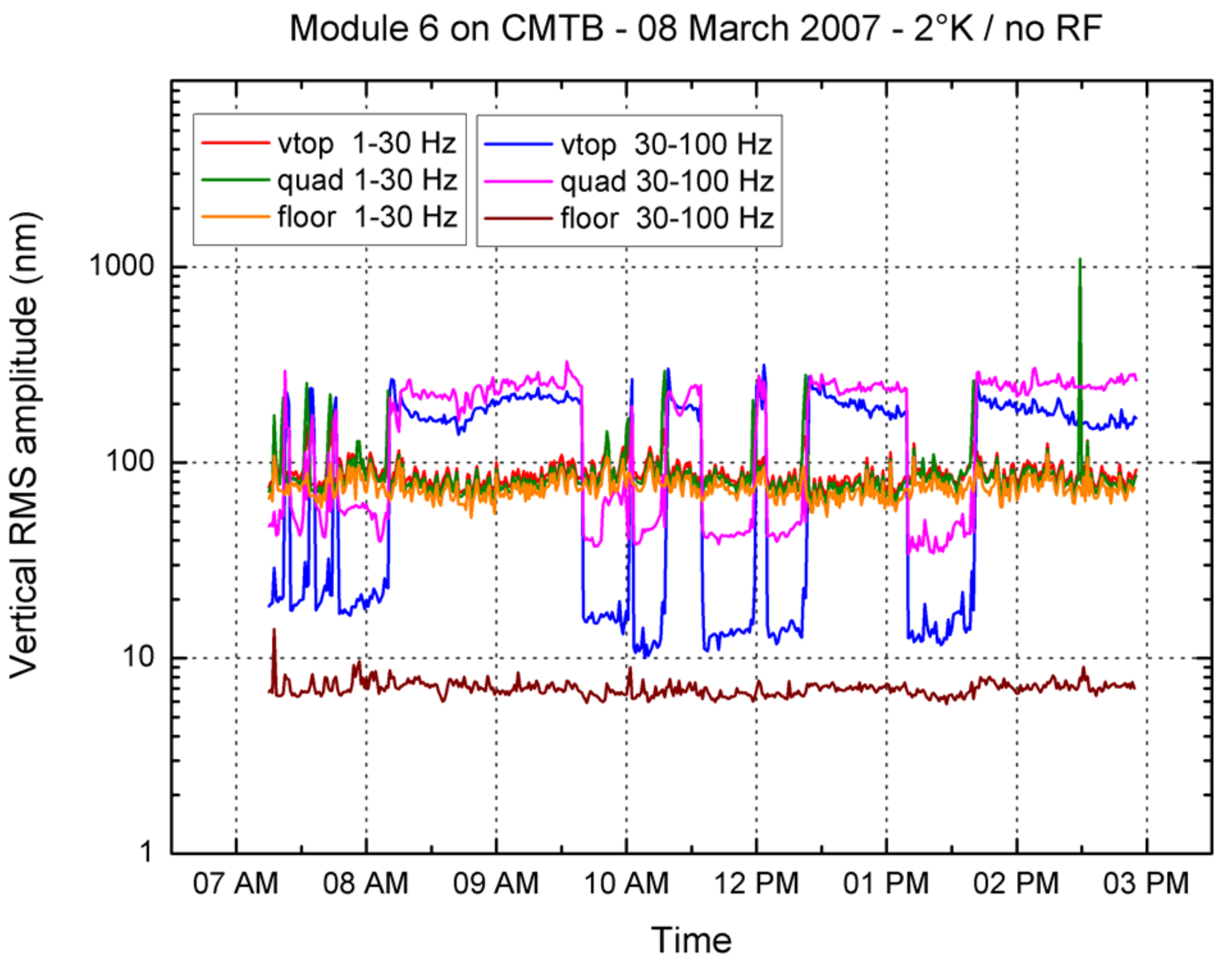
In the low frequency band the quadrupole motion tracks the ground vibration level. Slight amplitude differences are related mainly to the mechanical transfer function of the module on its support system. Non perfect equalization of the sensor response can also affect the accuracy. Quad RMS overestimated because of the low resonant frequency (4.14 Hz) of this geophone at room temperature.



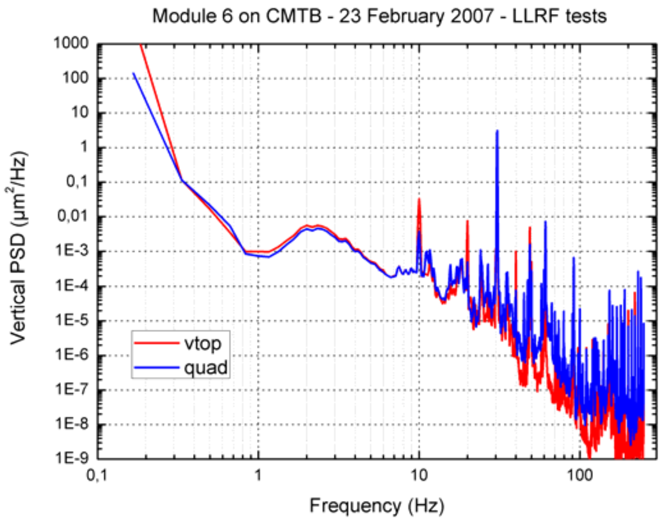
Quadrupole vibrations – Cold steady state – no RF

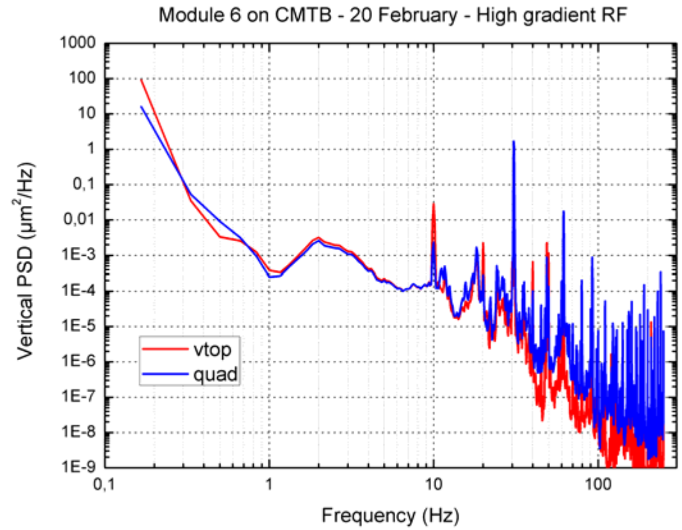
RMS analysis

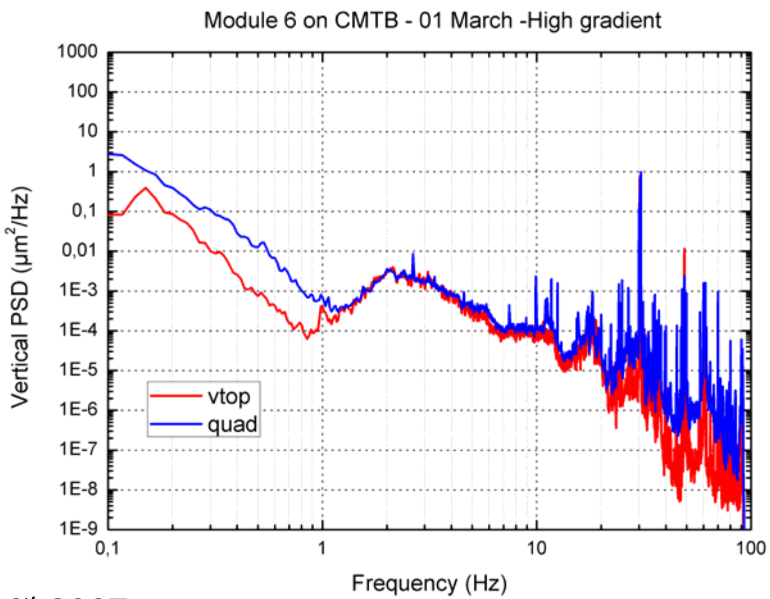
Ground motion tracking confirmed at low frequencies, with ~10% quad/gnd and top/gnd rms ratios. Large vibration amplitude at high frequency from the CMTB cryogenic plant. The refrigeration system doesn't affect the quadrupole stability at low frequency (f<30 Hz). High frequency noise to be checked after the solution of CMTB cryoplant problems.



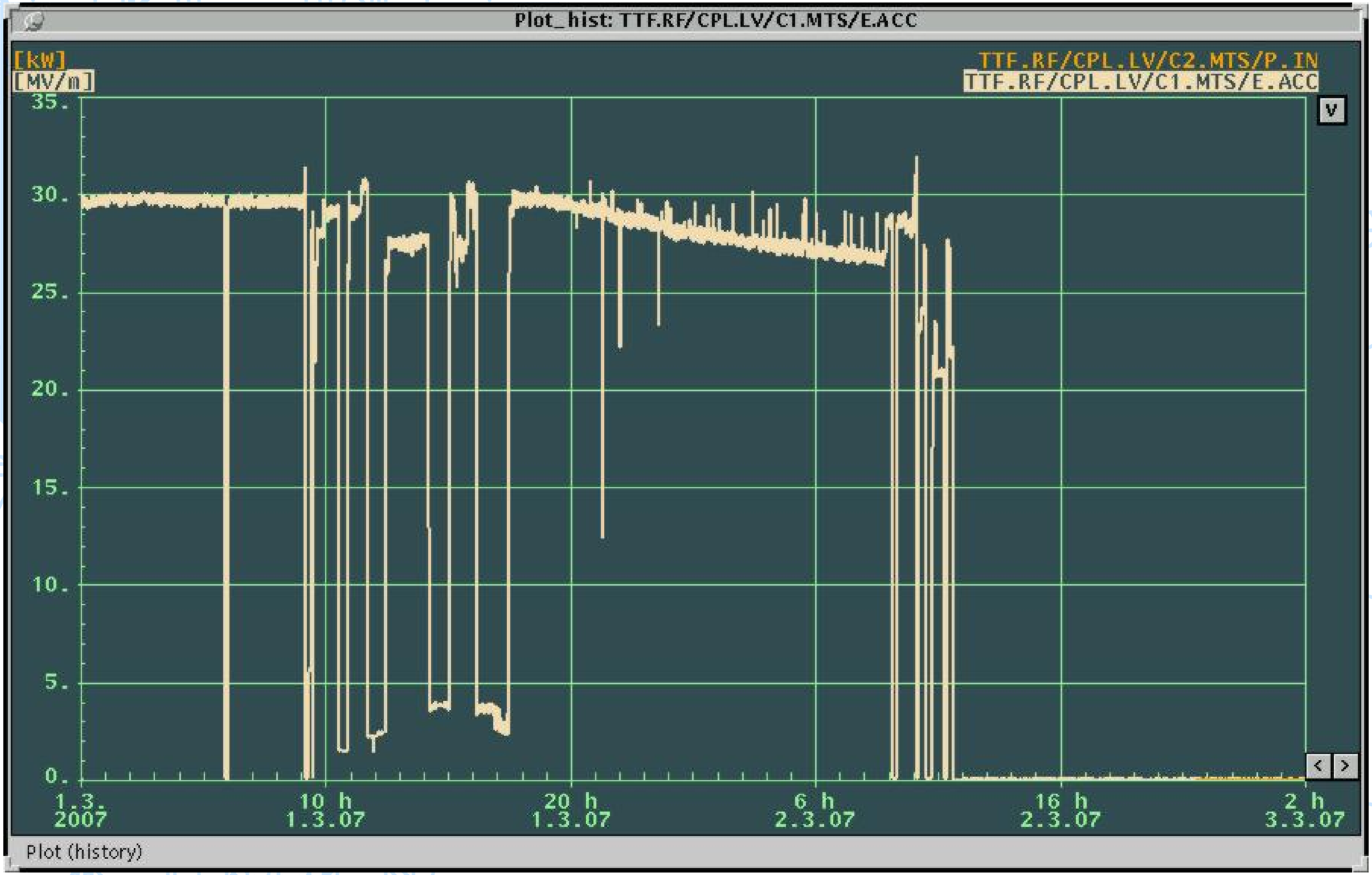
Quadrupole vibrations – LLRF tests and High gradient







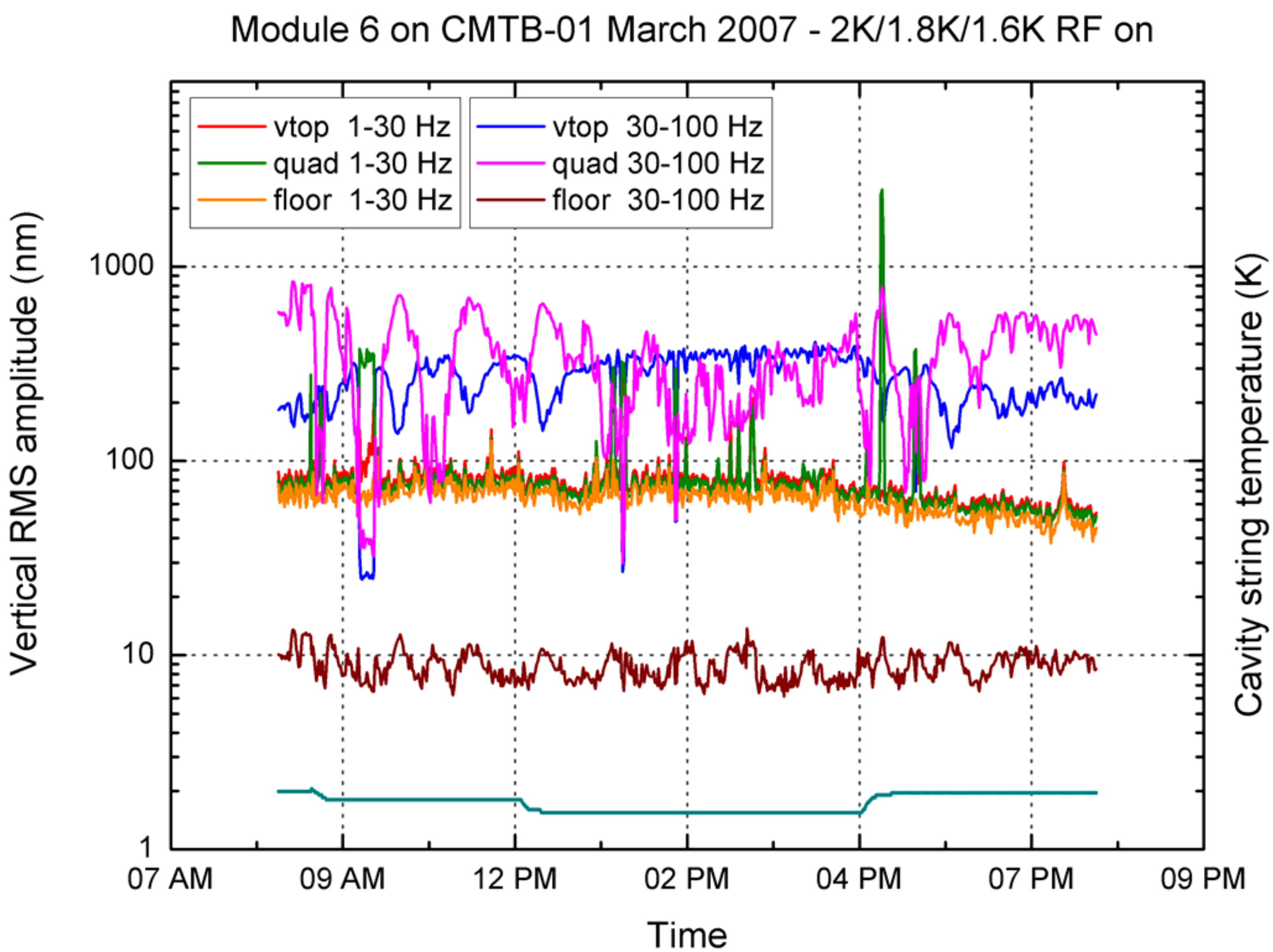
Quadrupole vibrations – RF high gradient – 2K/1.8K/1.6K



Quadrupole vibrations – RF high gradient – 2K/1.8K/1.6K

RMS analysis

Ground motion tracking confirmed at low frequencies. Usual large vibration amplitude at high frequency.
The high gradient RF operation doesn't affect the quadrupole stability.



Conclusions

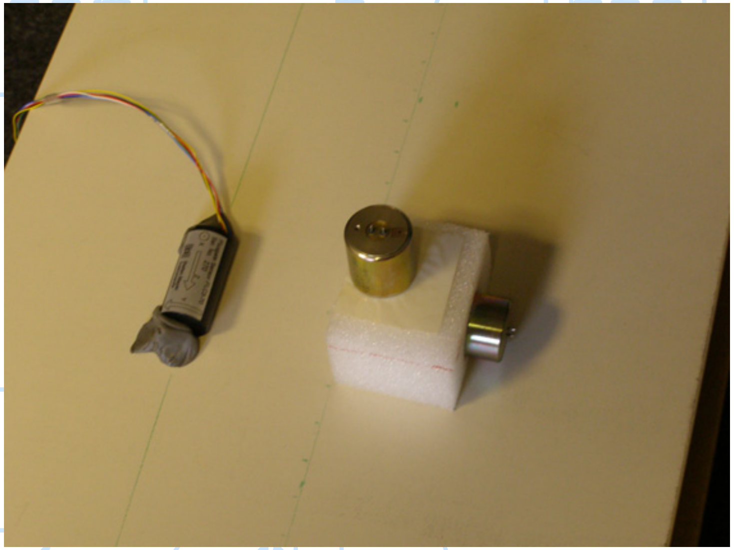
Geophone test at 4K

- classic 4.5 Hz industrial geophone can operate at 4K without any loss of sensitivity
- in-situ high accuracy calibration procedure demonstrated
- a new tool for low frequency vibration investigations at cryogenic temperatures

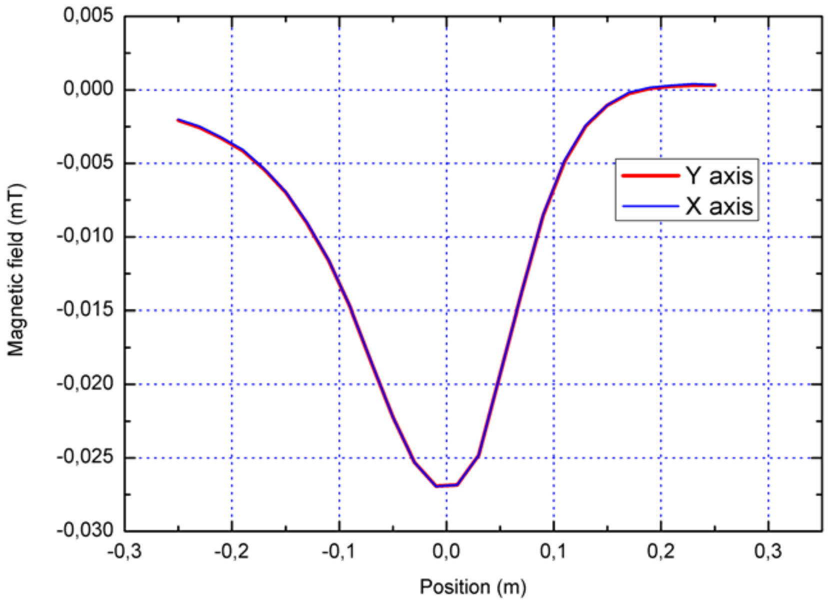
Quadrupole vibration measurements at 4 K

- low frequency (1-100 Hz) quadrupole vertical stability is not affected by high gradient RF operation
- quadrupole vertical stability is not affected by the refrigeration system at frequencies up to 30 Hz; results not conclusive at higher frequency because of the present limitations of the CMTB cryo plant.
- needed comparison with operation in the FLASH linac. Can we keep the geophones aboard Module 6?
- the results will be cross-checked with laser interferometry on Module 8 at the end of the year.

Can the geophone fringing field kick the FLASH beam?



Vertical/horizontal geophone pair configuration as simulated in our lab. The fringing field is measured with a 3-axis fluxgate magnetometer.



Transverse magnetic field (X,Y) measured along the equivalent beam axis (Z)

Discussion

The integrated field along the beam axis is < 0.01 mTm. The kick, at 500 MeV, from a 300 μm misalignment (XFEL tolerance) of the adiacent quad is more than 15 times larger (source: W. Decking). Conclusion: geophones could be safely installed in the FLASH linac.